MODELLING FOR THERMAL CONTROL OF VACUUM PLASMA SPRAYING

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Abstract : Vacuum plasma spraying (VPS) is an industrial technique used to coat substrates with a wide range of materials for numerous applications. Historically, vacuum plasma spraying processes have been open-loop processes with, at most, closed-loop control of the spray parameters. Such processes would benefit from closed-loop control as the issues of process repeatability and coating quality could be addressed**.** This paper describes the modelling of a VPS process and presents a closed loop control strategy based on the model results. *Copyright © 2005 IFAC*

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1. INTRODUCTION

Surface treatments have been used since the earliest days of metalworking and in modern engineering practice their applications have become widespread. One common method of applying a coating to a surface is to spray the coating onto a substrate. Metal, ceramic, polymer or composite coatings manufactured by spraying techniques are used in a range of applications, such as corrosion, erosion and oxidation resistance, thermal barriers, bond coats, abradable seals, and in bioinert or bioactive orthopaedic applications (Fincke, *et al.*, 2001; Montavon and Coddet, 1996; Sampath, *et al.*, 2003; Sampath and Jiang, 2001; Zhao, *et al.*, 2003). Thermal barrier coatings are also becoming increasingly important for the gas turbine market (Vattulainen, *et al.*, 1998) as the need for environmental protection and cost effectiveness has demanded an increase in the efficiency of energy conversion, which is achieved by increasing the gas turbine inlet temperatures in order to decrease the specific fuel consumption. The use of thermal barrier coatings on gas turbine components allow higher turbine inlet temperatures - at present gas turbine temperatures can reach in excess of 1400°C compared to approximately 700°C in the 1940's (Wigren and Pejyrd, 1998). The benefits of a thermal barrier coating include increased lifetime of part, increased engine efficiency, and increased combustion temperature - all of which have commercial and environmental benefit (Hejwowski and Weronski, 2002; Wigren and Pejyrd, 1998).

One estimate values the global thermal spray market at 1.35 billion US dollars during 1997 (Petrovicova and Schadler, 2002) and a market of this size would benefit from developments in spray processes that could improve their efficiency and ultimately reduce production costs. Costs incurred by the rejection and replacement of imperfect coatings can account for 15% of their production costs (Vardelle and Fauchais, 1999). Thus, for manufacturers, the reproducibility and reliability of sprayed coatings are the main goals for ensuring quality standards are met and decreasing production costs (Fincke, *et al.*, 2001; Sampath,

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et al., 2003; Zhao, *et al*., 2003; Sampath and Jiang, 2001; Vardelle and Fauchais, 1999).

2. VACUUM PLASMA SPRAYING

VPS spraying employs a plasma torch, essentially a high temperature arc, in order to melt coating materials that are fed into the torch. A stream of inert gas flowing through the torch then carries or "fires" the molten particles from the torch to the substrate being coated. For this reason the torch is often referred to as a plasma "gun."

To create the conditions required to form a plasma, a suitable gas, typically argon, is passed through a high-current arc. At sufficiently high temperatures, the gas becomes ionised and collisions between electrons and ions generate radiant energy. In a plasma torch, constricting the arc changes the thermal balance and this raises the temperature substantially, usually to 15000 - 20000 K.

The very high temperatures in the plasma torch allow a wide range of materials to be sprayed, provided that the material melts without significant dissociation and a practical temperature interval exists between its melting and boiling points. The absence of direct substrate heating minimises the problem of work piece distortion and allows the use of low, as well as high, melting point substrates. The process is thus remarkably versatile; it may be used to spray metals and alloys, ceramics, cermets and plastics, while the substrate may be of metal, ceramic or plastic (Smart and Catherall, 1972). The process is improved by performing the plasma spraying in a vacuum. This reduces contaminate particles becoming part of the coating and thus greatly improves the coating purity. As a consequence, vacuum plasma spraying is used for high value added applications.

The heart of the system is the plasma torch (or gun), which is shown schematically in figure 1.

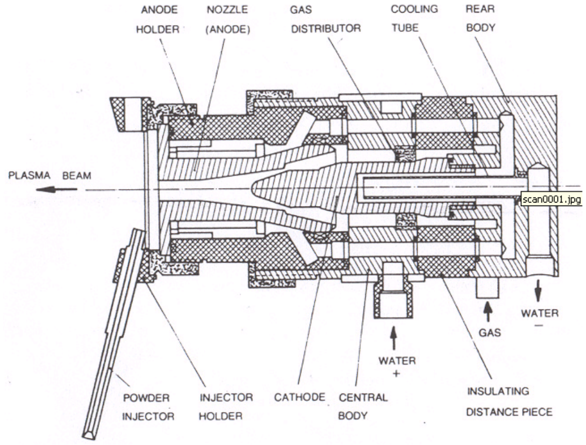

Fig. 1. Schematic diagram of plasma torch (Smart and Catherall, 1972).

The electrodes are contained within the gun and are shaped to give the required constriction while the arc gas and the feed material (generally powder) are fed in through different ports. The operation of the process and the efficiency of the gun, as well as the quality of the deposit, depend critically on such factors as electrode design, powder size, and substrate preparation. The highest quality coatings are generally obtained by automation of the spraying process. This is usually done with 5 or 6-axis robots, which are user programmed to scan the plasma gun over a substrate in a pre-defined path. Used in conjunction with an external axis, such as a turntable, a "carousel" of substrates can be sprayed during a single spraying session, rotating through each substrate to be sprayed. Being able to spray multiple substrates during a single session increases process repeatability and manufacturing productivity.

2.1 The vacuum plasma spraying unit

Research described in this paper is carried out on the A2000 PlasmaTechnik vacuum plasma spraying unit, which is shown in figure 2, can be split into three sub-systems, one responsible for operating the vacuum chamber, one for the robot inside the vacuum chamber, and one for the plasma gun mounted on the robot.

Fig. 2. A2000 plasma spray system.

During a typical spray run a substrate is mounted onto a carousel as shown in figure 3.

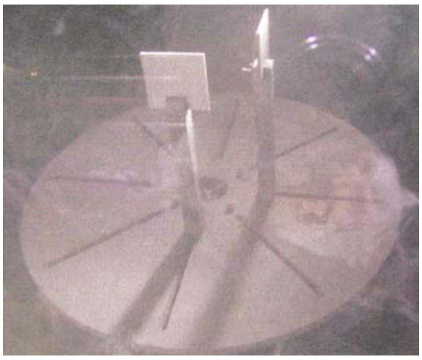

Fig. 3. Substrates mounted on a carousel.

The chamber door is shut by remote switch on the vacuum chamber system console and the chamber is pumped down to achieve a partial vacuum. Once a partial vacuum is reached the console auto-regulates the chamber pressure at a user-defined pressure using a flow of argon. Next, the console operating the plasma gun system is switched on and all the spray parameters are set for spraying according to the "recipe" for a particular coating. The spray parameters are the argon, hydrogen, helium, nitrogen flow rates, the powder feeder settings, and the arc current being supplied to the plasma gun. Once these parameters have been set the plasma gun is switched on and once the system has settled to its set point, defined by the spray parameters, the robot is switched on at the robot control console. Different spray programs can then be uploaded to the robot depending on the spray pattern and duration required for a particular coating for a particular substrate. Typically a spray run will last from two to four minutes. Once the spray run has finished the chamber is returned to atmospheric pressure, opened and the substrate removed from the carousel.

3. COATING QUALITY

The major factor that determines whether a surface treatment is effective and of high quality is the microstructure of the coating (Devasenapathi, *et al.*, 2001; Friis and Persson, 2003; Sampath and Jiang, 2001; Wang, *et al.*, 2001). Different microstructural features will be required for different coating uses and whether or not a desired microstructure is achieved will determine whether or not a high quality, effective coating is produced. To illustrate this, the desired microstructure of a thermal barrier coating is discussed. First, the microstructure of the top coat (the top coat is the actual thermal barrier coating, which is usually sprayed on top of a substrate bond coat to enhance adherence) is considered. As molten particles impact on a substrate, they form "splats" that rapidly cool down and crack due to the quench stresses and the thermal expansion coefficient in conjunction with the material properties (Bianchi, *et al.*, 1997; Chraska and King, 2002; Sampath and Jiang, 2001; Wigren and Pejyrd, 1998) as shown in figure 4.

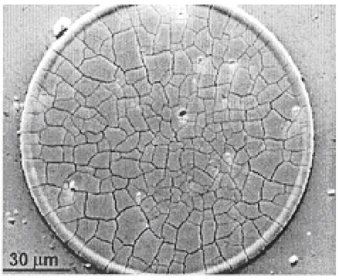

Fig. 4. A solidified zirconia splat (Chraska and King, 2002).

These splat pile up on top of each other during the spraying process and give rise to a second microstructural feature referred to as horizontal delaminations. These can be either separation between splats or just wide splat boundaries. Figure 5 shows vertical micro cracks and horizontal delaminations in a splat.

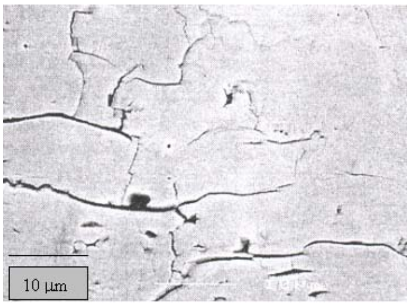

Fig. 5. Vertical micro cracks and horizontal delaminations in a splat (Wigren and Pejyrd, 1998).

Wigren and Pejryd (1998) have shown that these micro features, and especially the horizontal delaminations, can be the critical factors determining the coating performance, as illustrated by the relationship of the thermal shock life and the length of horizontal delaminations of figure 6.

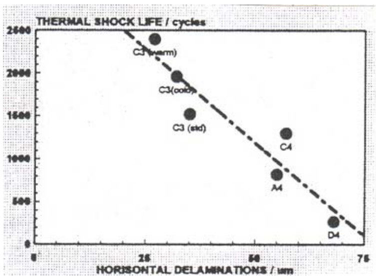

Fig. 6. Thermal shock life versus horizontal delaminations.

One of the most critical areas of a thermal barrier coating is the adherence between the bond and topcoat. If this area is exposed to high temperatures, thermally grown oxides will form, as shown in figure 7. It is a general belief that the growth rate of this oxide film dictates the life of a thermal barrier coating (Wigren and Pejyrd, 1998).

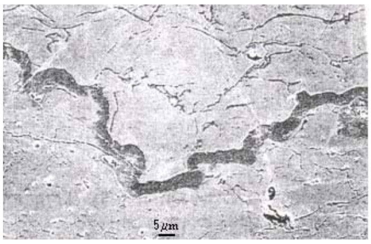

Fig. 7. Dark band highlights an alumina thermally grown oxide film of approximately 5µm thickness (Wigren and Pejyrd, 1998).

In conjunction with the interface oxide growth, internal oxidation of the bond coat may also take place. This however is minimised when a vacuum plasma spraying process is being used (Wigren and Pejyrd, 1998).

It has been well documented that the substrate surface temperature during spraying is a key parameter controlling the microstructure evolution of the coating (Chraska and King, 2002; Fukumoto, *et al*., 2001; Jiang, *et al*., 2001; Sampath and Jiang, 2001; Sampath, *et al*., 2003). Therefore, a temperature control strategy is appropriate to address the problem of coating quality and reproducibility.

4. MODELLING RESULTS

4.1 Theoretical modelling

A model of the thermal flows within the VPS chamber is necessary in order to design a feed forward controller for regulating substrate surface temperature during spraying. The feed forward control is combined with feedback to correct for modelling errors. Given the range of processing conditions the model provides suitable gains for the feedback. Such a model will allow a compilation of gain schedules for a range of processing conditions which will prove to be a more efficient implementation of control than simply tuning a controller for a given processing condition.

The plasma gases form a thermal field within the VPS chamber. The position of the substrate being sprayed within the chamber will determine its steady state temperature. In order to predict the rate and amplitude of substrate heating, a model of this thermal field must be developed. Zhao *et al.* (Zhao, *et al*., 2000a, Zhao, *et al*., 2000b) have produced a computational fluid dynamic (CFD) model for a similar VPS process. In this model, an energy balance analysis of the VPS process was used to calculate the exit temperatures and velocities of the plasma gases at the plasma gun, which are subsequently used as boundary conditions in a CFD model of the plasma gas temperature and flow. Zhao qualitatively validated his model based on trends observed in experimental measurements.

In this paper, Zhao's energy balance method was used in order to produce a thermal model of the VPS using FLUENT v6.1 CFD software, capable of realising the thermal field inside the vacuum chamber for any set of processing conditions.

A two-dimensional, axisymmetric grid representing the VPS chamber, plasma gun, and substrate was created using GAMBIT, the FLUENT geometry tool. This grid was used to calculate the thermofluid properties of the flow from the plasma gun, modelling the flow as an axisymmetric hot Argon gas jet from an orifice. The governing equations of this model are as follows.

Conservation of mass. The rate of change of the fluid mass in any volume is equal to the overall fluid mass flux into the volume. Therefore the mass conservation equation is:

$$\Delta\rho(r,z)/\delta\mathrm{t} = -\nabla\cdot(\rho(r,z)v(r,z)) \qquad (1)$$

where $\rho(r,z)$ is the local density of the argon gas as a function of axial and radial postion since this is a 2-d axisymmetric case, t is the time, ∇ is the vector differential operator and v is the gas velocity vector as a function of radial and axial position (FLUENT, 2003).

Conservation of momentum. The rate of change of momentum of fluid within any volume is equal to the total body and surface forces produced by external means and acting on the fluid volume. Neglecting external body forces, the momentum conservation equation is

$$\mathrm{P}(r,z)\mathrm{dv}(r,z)/\mathrm{d}t = -\nabla p(r,z) + \nabla\cdot\tau(r,z) \qquad 2)$$

Where p is the pressure as a function of radial and axial position and τ is the stress tensor as a function of radial and axial position (FLUENT, 2003).

Conservation of energy. FLUENT solved the energy equation in the following form

$$\delta(\rho E)/\ \delta t + \nabla\cdot(v(r,z)(\rho(r,z)E + p(r,z)) = \nabla\cdot(k\nabla T(r,z) + (\tau(r,z)\cdot v(r,z))) + S_{\mathrm{h}} \qquad (3)$$

where E is the energy, k is the thermal conductivity, T is the argon gas temperature as a function of radial and axial position, and S_{h} represents the radiative heat transfer model. The first two terms on the right hand side represent the energy transfer due to conduction and viscous dissipation, respectively (FLUENT, 2003).

The gas jet is modelled as a turbulent flow and the velocity components and thermal conductivity are treated as the sum of a mean value and a fluctuating part which is calculated using the realizable k-ε model (FLUENT, 2003). This requires inputs of turbulent intensities and characteristic lengths at inlets and outlets. These were taken as 5% and the radius of the inlet or outlet, respectively (Zhao, *et al*., 2000a). An example output from the CFD model is shown in figure 8.

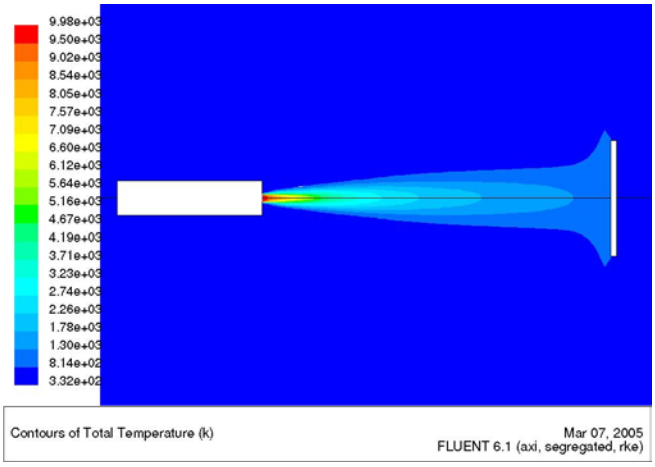

Fig. 8. Temperature contour plot of the VPS chamber (2-D axisymmetric about the spray axis)

The results taken from this CFD model were then validated against experimental measurements taken.

4.2 Experimental validation

Thermocouple measurements of the temperature inside the VPS chamber were taken at 25 mm intervals along the plasma gun spray axis between spray distances of 300mm (1.6m from the front of the chamber) and 600 mm (2.2m from the front of the chamber) downstream of the gun. The steady state temperatures for each axial point are plotted on figure 9 which illustrates that the axial temperatures follow an exponential relationship with axial spray distance.

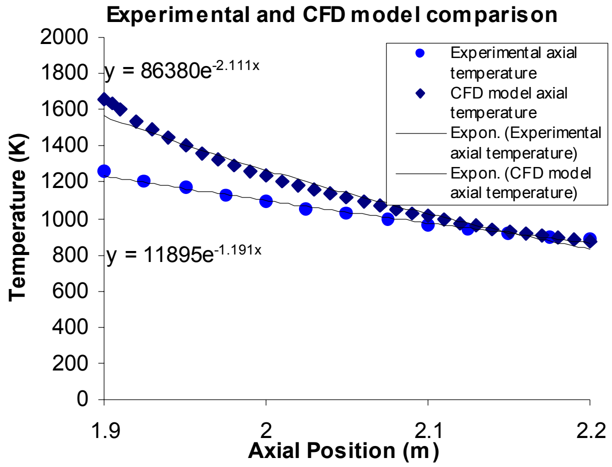

Fig. 9. Plot of plasma gas temperatures versus axial spray distance at steady state for experimental and CFD models.

The theoretical and experimental results show qualitative agreement and suggest that an experimentally validated thermal field function could be generated from CFD modelling results. This function would describe the thermal field inside the chamber for a given set of spray parameters i.e. $T_f\ (r, \theta, z) = f\ (I,\ F_{H2},\ F_{Ar},\ P)$ where $T_f\ (r, \theta, z)$ is the thermal field inside the chamber in cylindrical polar coordinates,I is the arc current, F_{H2} is the hydrogen flow rate, F_{Ar} is the argon flow rate, and P is the chamber pressure, in order to produce a global model of the thermal field. This will then enable the calculation of the heat transfer to a particular substrate, and the surface temperature it will attain over time.

5. CONTROLLER DESIGN

The control aim is to regulate the substrate surface temperature according to a desired temperature or temperature grading during the spraying process. The control variable is the position of the substrate within the chamber. The range of position is limited by extremes beyond which the coating quality degrades for example a typical range which was used as the basis for this work is 300 to 600mm downstream of the plasma gun.

For any particular "spray recipe", i.e. particular set of processing parameters, the thermal field that will exist in the chamber is known from the CFD model. The mean heat transfer coefficient across the substrate surface is then calculated using the empirical relation described in Martin's work (Martin, 1997)

$$Nu/Pr^{0.42} = (D/r)((1-1.1D/r)/(1+0.1(H/D - 6)D/r))0.54Re^{0.667} \qquad (4)$$

where Nu is the Nusselt number, Pr is the Prandtl number, D is the plasma gun exit orifice diameter, H is the distance between the exit orifice and the substrate, and r is the distance between the jet impingement point on the substrate and the point of interest.

The Nusselt and Prandtl numbers can be expressed, respectively

$$Pr = C_p \mu / k \qquad (5)$$

$$Nu = hL / k \qquad (6)$$

Where C_p is the specific heat capacity of the gas, μ is the dynamic viscosity of the gas, k is the thermal conductivity of the gas, L is the characteristic length, and h is the heat transfer equation. The only unknown quantity in equations (4), (5) and (6) is h so substituting equations (5) and (6) into (4) allows for the calculation of the heat transfer coefficient h.

Knowing the substrate initial position and temperature then permits the calculation of the heat flux to the substrate from the thermal field generated by the plasma gun, allowing the calculation of the substrate surface temperature *i.e.* a function can be derived relating substrate surface temperature and position for any given set of processing conditions. This then makes possible the design of a position trajectory, i.e. a feed forward control, during the spraying in order to regulate the surface temperature to meet the control aim. A temperature sensor, such as a thermocouple, pyrometer, or thermal imaging camera, to measure the substrate surface temperature will allow a feed back control to correct any deviations from the desired surface temperature. It is important to note that the heat flux cannot simply be determined from the CFD model since it can only calculate it in the steady state case – a constant substrate surface temperature, i.e. the CFD model does not account for the substrate surface heating up.

6. CONCLUSIONS

Substrate surface temperature has been identified as a key parameter controlling the coating quality of vacuum plasma sprayed substrates. It has been proposed that a closed loop control of the substrate surface temperature during spraying will address manufacturing problems of coating reproducibility and quality. An experimentally validated thermal model (including heat transfer coefficient calculation), as opposed to Zhao's qualitatively validated model, allows the feedback gain to be determined for any given set of processing conditions.

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